Ten Years of Satellite Infrared Radiance Monitoring With the Met Office NWP Model

Roger W. Saunders, Thomas A. Blackmore, Brett Candy, Peter N. Francis, and Tim J. Hewison

***Abstract*— Satellite sounder infrared radiances are among the most important contributions to the global observing system and have been assimilated into global numerical weather prediction (NWP) analyses for many years. They are also used as fundamental climate data records for climate monitoring. Prior to assimilation or producing climate records, the radiances should have all residual instrument biases removed. One way of estimating the mean biases is to continuously monitor the measured radiances against the NWP model equivalent radiances. This article is an extension of one published in 2012 which documented these biases for three years but now the time span of the monitoring has extended to beyond ten years, allowing the long-term stability of the instruments to be assessed. Data from high-resolution infrared sounder (HIRS), Advanced Along Track Scanning Radiometer (AATSR), and Spinning Enhanced Visible and Infrared Imager (SEVIRI), radiometers; atmospheric infrared sounder (AIRS), a spectrometer; and infrared atmospheric sounding interferometer (IASI), an interferometer, were included. Changes in mean biases and standard deviations were used to investigate the temporal stability of the bias and radiometric noise of the instruments over ten years. A double difference technique was employed to remove the effect of changes or deficiencies in the NWP system and radiative transfer (RT) model, which can contribute to the biases. The IASI and AIRS radiances were stable but with a different bias between the two instruments due to different versions of the RT model used. The SEVIRI radiometers were stable in most channels with the exception of the 13.4 μm channel. The HIRS instruments were subject to sudden changes in bias and increases in standard deviation compared with NWP simulations during the past decade.**

***Index Terms*— Calibration, numerical weather prediction (NWP), remote sensing, satellites.**

Nomenclature

AATSR	Advanced Along Track Scanning Radiometer.
AIRS	Atmospheric infrared sounder.
CrIS	Cross track Infrared Sounder.
ECMWF	European Centre for Medium range Weather Forecasts.
FCDR	Fundamental climate data record.
HIRS	High resolution infrared sounder.
IASI	Infrared atmospheric sounding interferometer.
JMA	Japan Meteorological Agency.
Metop	Meteorological Operational Satellite.
MSG	Meteosat Second Generation.
NOAA	National Oceanic and Atmospheric Administration.
NWP	Numerical weather prediction.
NPP	National Polar-orbiting Partnership.
RTTOV	Radiative transfer for TOVS (a fast radiative transfer model).
TOVS	TIROS Operational Vertical Sounder.
SEVIRI	Spinning Enhanced Visible and Infrared Imager.

Manuscript received March 29, 2020; revised June 18, 2020; accepted July 29, 2020. *(Corresponding author: Roger Saunders.)*

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This article has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors.

Digital Object Identifier 10.1109/TGRS.2020.3015257

I. Introduction

SATELLITE infrared radiances assimilated in global NWP models are now among the most important observation types, in terms of forecast impact, for operational NWP centers [1], [2] due to their global coverage in clear skies and over low cloud. The advanced infrared sounders, with higher spectral resolution (e.g., AIRS and IASI), also provide better vertical resolution for the profiles of temperature and water vapor as compared with those from microwave sounders, although the coverage of the latter is better as they are less affected by clouds.

The time series of these advanced infrared radiances are now sufficiently long to provide monitoring of atmospheric changes over several decades for the high spectral resolution measurements and as long as 40 years for the conventional filter radiometers. These data sets are now beginning to be reprocessed in an attempt to remove the instrument-related biases in the radiances for assimilation in atmospheric reanalysis and as fundamental climate data records [3] for monitoring of Earth's climate.

As part of the operational processing at the Met Office, the radiances are ingested in the global NWP suite which provides a continuous record of the differences between the measured radiances and their equivalent values computed from the model fields coupled with a fast radiative transfer (RT) model. The differences can be due to deficiencies in the instrument calibration or anomalies in the instrument operation (e.g., pointing errors). The differences can also be due to the NWP fields having consistent biases in their representation of the atmosphere/surface (e.g., water vapor concentration profile, surface skin temperature, and so on). When considered globally, these biases in NWP model fields do not normally change rapidly in time except when a new version of the NWP system is implemented. The RT model may also introduce small biases due to uncertainties in the spectroscopic parameters and errors in the instrument spectral response function assumed.

In addition, the effects of other variable gases (e.g., ozone) can be a factor as only climatological mean profiles are assumed in most NWP models and so biases may be seen for those channels which are affected by these trace gases. The analysis of the observed minus simulated differences hereafter referred to as O-B provides insight into both instrument anomalies and the changes in the accuracy of the NWP temperature and water vapor fields over the decade.

These NWP and RT model biases should, to the first order, remain the same for different instruments with channels at similar wavelengths and so should cancel out when the biases between similar channels of two instruments inferred from the same NWP system are differenced. This is referred to as a "double difference" in this article. It is only when interpreting the absolute value of the observed–simulated radiance biases that the NWP and RT model biases need to be considered. Before assimilation in a variational analysis, which assumes unbiased Gaussian statistics, these mean biases are removed using a correction scheme [4], [5].

To support the Global Space-based Inter-Calibration System (GSICS) [6], the Met Office has been monitoring the infrared sounders for the past ten years to understand the long-term variation of the instrument and NWP system biases. An initial assessment was published after the first three years of monitoring [7] and this article extends the results over a much longer time period from November 2008 to December 2019. The methodology used is described in [7] and so is not described in detail here.

There are several other sources where satellite radiance biases are monitored against NWP models or reanalysis [8]–[11] and some analysis is presented here of the reasons for the differences in the biases reported here.

The satellite data processed and NWP system changes are described in Section II, and an analysis of the results is given in Section III followed by a summary in Section IV.

II. Satellite Data Processed and NWP System Changes

The instruments processed in this study over the ten-year period are listed in Table I and the channels reported for each sensor in this article are given in Table II. Note that, however, many more channels were monitored for each instrument as documented in [7, Table I] and the decadal mean statistics for all the channels processed are provided in the supplementary materials. NOAA-17 HIRS ceased providing reliable data from the end of January 2013. NOAA-19, however, is still providing HIRS data in December 2019. Both the Metop-A HIRS and IASI instruments worked throughout the ten-year period reported here, although the HIRS instrument has become anomalous since 2017. The HIRS on Metop-B has been problematic and only a short period of these data were processed during 2016 and 2017. The Metop-B IASI, however, has been working well and is monitored from September 2013 allowing a long comparison with the Metop-A IASI. The recently launched Metop-C IASI data are included in the plots but were only processed from April 9, 2019. The monitoring of the microwave sounders was not continued beyond that reported in [7] and so only the infrared instrument biases are reported here.

TABLE I
Instruments and Channels for Which Bias Monitoring Statistics Were Collected between 2009 and 2019

Geostationary Satellite	Instrument	Channels	Source	Period
Meteosat-9	SEVIRI	8 IR	EUMETCAST	19 Nov 2008-21 Jan 2013
Meteosat-10	SEVIRI	8 IR	EUMETCAST	21 Jan 2013-20 Feb 2018
Meteosat-11	SEVIRI	8 IR	EUMETCAST	20 Feb 2018-31 Dec 2019
Polar-orbiting Satellite	**Instrument**	**Channels**	**Source**	**Period**
Metop-A	IASI	See Table II	EUMETCAST	19 Nov 2008 – 31 Dec 2019
	HIRS	9 IR	EUMETCAST	19 Nov 2008 – 31 Dec 2019
Metop-B	IASI	See Table II	EUMETCAST	15 Sep 2013 – 31 Dec 2019
	HIRS	9 IR	EUMETCAST	1 Jan 2016 – 16 Feb 2017
Metop-C	IASI	See Table II	EUMETCAST	1 May 2019 – 31 Dec 2019
Aqua	AIRS	See Table II	NESDIS	19 Nov 2008 – 31 Dec 2019
NOAA-17	HIRS	9 IR	NESDIS	19 Nov 2008 – 30 Jan 2013
NOAA-19	HIRS	9 IR	NESDIS	14 July 2009 – 31 Dec 2019
ENVISAT	AATSR	3 IR Nadir 3 IR Fwd	FTP ESRIN	1 Sep 2010 – 8 April 2012

TABLE II
Infrared Channel List for the Sensors Reported Here

Sensor	Channel number	Central frequency cm^{-1}
IASI	246	706.25
IASI	1133	928
IASI	3522	1525.25
AIRS	198	706.14
AIRS	787	917.31
AIRS	1756	1524.35
HIRS	4	703
HIRS	8	899
HIRS	12	1528 - 1533
SEVIRI	11	748
SEVIRI	9	927
SEVIRI	5	1588
AATSR	2	921

Table I documents the periods for which the data were available with gaps due to operational problems with various instruments. These data sets have been generated from November 19, 2008 (just before the Meteosat-9 SEVIRI decontamination was performed) up to December 31, 2019 for all sensors still functioning. The AATSR data record started from September 2010 and ceased on April 8, 2012 when all contact with the ENVISAT satellite was lost. The sources of the data are also indicated in Table I. Note that only the global data sets from the space agencies are included here, not the EUMETSAT rebroadcast or EARS data or locally received HRPT/HRIT data.

The radiances are processed as part of the operational NWP data assimilation system at the Met Office which includes selecting a limited number of channels, thinning the spatial coverage, and passing through a 1D-Var preprocessor [12]. The simulated radiances are computed every 3 h from 6-h forecast fields of temperature and water vapor profiles and surface variables interpolated to the appropriate time of the observation. Table II lists the channels specifically analyzed here using the normal channel numbering convention for each instrument, although note that all the channels are documented in the supplementary material. As in [7], the criterion for the selection of the IASI and AIRS channels was proximity to the HIRS and/or SEVIRI channel central wavelengths so that comparisons could be made between different instruments at similar wavelengths. Variables such as incidence angle, latitude, and longitude are all stored with each observation in the bias data sets to enable further analysis.

The Meteosat SEVIRI data set covers the full Earth disk seen by SEVIRI. The data set used for this study samples every fourth pixel and scan line, and a cloud detection scheme [13] is used at the Met Office for generating its clear sky and cloud products for NWP assimilation and nowcasting applications.

The global polar orbiter data are received from NOAA and EUMETSAT as calibrated level 1B radiances. They are passed through a 1D-Var preprocessor which allows a quality control check and a cloud test [14] to be applied to all the infrared sounders. Note that for this quality control step only, the radiances have their mean bias with respect to the model background removed. The IASI channel subset is then taken from the clearest of the four fields of view within the corresponding Metop-A AMSU-A field of view. The AIRS radiances are taken from the warmest field of view within an Aqua AMSU-A field of view. One source of possible bias is due to undetected cloud in the measured radiances and so for this study, it is important to have very strict cloud detection criteria. As a check on the removal of cloudy pixels, histograms of the clear sky radiances were examined and were shown to be Gaussian in shape and did not exhibit a "cold tail." Only radiances which have passed the quality control checks and converged in 1D-Var are used for computing the O-B bias. To be consistent throughout the ten years, the cloud detection methodology was kept the same where possible. However, the loss of some channels forced changes to be made in the HIRS and AIRS timeseries.

AATSR radiances are averaged values over ten arc minute cells and only cloud-free data are provided in the data sets using the method described in [15]. The ENVISAT overpass time was in a morning orbit similar to that of Metop.

Over the ten-year period, the Met Office NWP system has undergone many changes to increase the horizontal and vertical resolution and improve both the model physics, dynamical core, and the data assimilation, and this will affect the simulated radiances computed. Similarly, the RT model, RTTOV [16], and satellite data preprocessing have been updated during this period which can lead to changes in the computed bias. These changes are documented in Table III and where a sudden change can be ascribed to an NWP system change rather than an instrument anomaly, this is noted in the analysis.

TABLE III

TIMELINE OF CHANGES IN MET OFFICE FORECAST MODEL

Date	Model change	Category
20 Aug 2009	Start assimilation of NOAA-19 HIRS and AMSU radiances.	Change in observations
10 Nov 2009	Change of model levels from 50 to 70 and model top raised from 0.1hPa to 0.01hPa.	Change in model
10 Nov 2009	Change in bias correction of radiosonde relative humidity.	Change in observations
17 Dec 2009 to 9 Feb 2010	NOAA-17 HIRS not assimilated.	Change in observations
9 Mar 2010	DMSP F-16 SSMIS window channels assimilated operationally – clear scenes only over ocean.	Change in observations
2 Nov 2010	Modify AIRS channel selection and assumed observation errors.	Change in observations
2 Nov 2010	SSMIS channels 21,22 introduced to improve mesospheric/upper stratospheric analysis .	Change in observations
2 Nov 2010	Introduce Meteosat-9 clear sky window and water vapour channel radiances.	Change in observations
20 July 2011	Introduce GOES-E+W clear sky window and water vapour channel radiances.	Change in observations
20 July 2011	Use more IASI channels over land.	Change in observations
20 July 2011	Change in humidity control variable from relative humidity to normalized pseudo relative humidity.	Change in model
28 March 2012	Hybrid DA updated to use MOGREPS-G	Change in model
17 Sept 2012	Upgrade to RTTOV-9 in data assimilation	Change in RT
23 Jan 2013	Moved to RTTOV-9 for bias stats presented here	Change in RT
30 April 2013	CrIS and ATMS assimilated	Change in observations
15 July 2014	Increase in model resolution 25 km to 17 km. New dynamics model ENDGAME implemented.	Change in model
1 Jan 2016	Change to IASI cloud detection thresholds	Change in observations
15 Mar 2016	VarBC introduced for all radiances. Aircraft Relative Humidity assimilated.	Change in model
8 Nov 2016	More IR radiances assimilated over land. Added FY-3B MWHS radiances.	Change in observations
11 July 2017	Upgraded to RTTOV-11. Increased model horizontal resolution to 10km.	Change in RT/Change in model
13 Feb 2018	Assimilated GMI radiances. IASI and ATOVS thinning changed.	Change in observations
25 Sep 2018	Upgraded to RTTOV-12. Cloud affected AMSU-A assimilated.	Change in RT/Change in observations

III. Analysis of Radiance Biases

The sensitivity of the different instruments' biases against a range of variables (e.g., scan angle, scene temperature, region) has not changed significantly from those reported in [7] and so what we report here are only the timeseries of the O-B values where there has been a significant change observed. The time series plots of the globally averaged mean O-B values presented here are a way to determine the stability of an instrument, particularly if the double difference technique [7] is employed to remove the effect of NWP system changes. Tables IV–VI provide a summary of the annual mean O-B

TABLE IV
ANNUAL MEAN O-B STATS FOR CHANNELS CENTERED ON 14.2 μm CO2 BAND EXCEPT FOR SEVIRI WHICH IS AT 13.4 μm

Year	IASI-A 246	IASI-B 246	IASI-C 246	AIRS 198	NOAA-17 HIRS 4	NOAA-19 HIRS 4	METOP-A HIRS 4	METOP-B HIRS 4	METEOSAT SEVIRI 11
2009	0.17			-0.55	0.14	-0.24	-0.26		-1.36
2010	-0.02			-0.62	-0.16	-0.46	-0.52		-2.17
2011	-0.08			-0.68	-0.22	-0.45	-0.53		-2.73
2012	-0.13			-0.70	-0.16	-0.45	-0.53		-3.21
2013	-0.18	-0.20		-0.72		-0.56	-0.49		-1.47
2014	-0.19	-0.23		-0.73		-0.90	-0.48		-1.09
2015	-0.22	-0.27		-0.73		-0.90	-0.48		-1.14
2016	-0.25	-0.31		-0.82		-1.05	-0.57	-1.22	-1.08
2017	-0.31	-0.29		-0.85		-1.02	-0.75		-1.74
2018	-0.40	-0.30		-0.88		-1.05	-0.85		-0.61
2019	-0.48	-0.39	-0.46	-0.91		-1.07	-0.66		-0.52
Mean	**-0.19**	**-0.29**	**-0.46**	**-0.74**	**-0.10**	**-0.43**	**-0.47**	**-1.22**	

TABLE V
ANNUAL MEAN O-B STATS FOR CHANNELS CENTERED ON 10.8 μm WINDOW

Year	IASI-A 1133	IASI-B 1133	IASI-C 1133	AIRS 787	NOAA-17 HIRS 8	NOAA-19 HIRS-8	METOP-A HIRS-8	METOP-B HIRS-8	METEOSAT SEVIRI-9	ENVISAT AATSR-2
2009	-0.28			-0.01	-0.72	-0.73	-0.70		-0.28	
2010	-0.30			-0.11	-0.80	-0.82	-0.78		-0.39	-0.23
2011	-0.33			-0.07	-0.79	-0.81	-0.76		-0.39	-0.18
2012	-0.31			0.02	-0.65	-0.78	-0.73		-0.36	-0.14
2013	-0.28	-0.26		0.19		-0.58	-0.73		-0.26	
2014	-0.26	-0.26		0.26		-0.25	-0.71		-0.23	
2015	-0.25	-0.25		0.32		-0.22	-0.71		-0.25	
2016	-0.21	-0.23		0.26		0.03	-0.49	-0.14	-0.27	
2017	-0.22	-0.22		0.29		-0.01	0.07		-0.27	
2018	-0.24	-0.23		0.37		-0.08	0.14		-0.25	
2019	-0.22	-0.21	-0.22	0.51		-0.14	0.17		-0.22	
Mean	**-0.26**	**-0.23**	**-0.22**	**0.19**	**-0.74**	**-0.79**	**-0.73**	**-0.14**		**-0.18**

TABLE VI
ANNUAL MEAN O-B STATS FOR CHANNELS CENTERED ON 6.5 μm WATER VAPOR BAND

Year	IASI-A 3522	IASI-B 3522	IASI-C 3522	AIRS 1756	NOAA-17 HIRS 12	NOAA-19 HIRS-12	METOP-A HIRS-12	METOP-B HIRS-12	METEOSAT SEVIRI-5
2009	-0.80			0.15	-0.09	-0.34	-0.40		-0.24
2010	-0.42			0.35	0.13	-0.09	-0.18		-0.02
2011	-0.16			0.70	0.38	0.20	0.11		0.19
2012	-0.03			0.80	0.47	0.32	0.19		0.18
2013	0.41	0.60		1.26		0.58	0.45		0.55
2014	0.50	0.54		1.35		0.62	0.47		0.62
2015	0.36	0.44		1.35		0.66	0.42		0.62
2016	0.48	0.52		1.46		0.78	0.69	0.59	0.80
2017	0.55	0.59		1.52		0.82	1.49		0.82
2018	0.66	0.70		1.58		0.84	2.48		0.61
2019	0.67	0.72	0.66	1.71		0.87	2.86		0.67
Mean	0.20	0.59	0.66	1.12	0.23	0.14	0.20	0.59	

differences for each of the instruments for the three wavelength regions considered here in Table II. The annual means are only computed where each instrument had a significant amount of time in that year. For HIRS, the means are only computed up until the first anomaly occurred.

Fig. 1 shows a plot of the global mean biases between the Metop-A IASI (IASI-A) and Metop-B IASI (IASI-B) window channels at 10.78 μm (928 cm^{-1}) from 2013 to 2019. The top panels show the mean differences and standard deviation of the differences from the NWP model equivalents, and it is

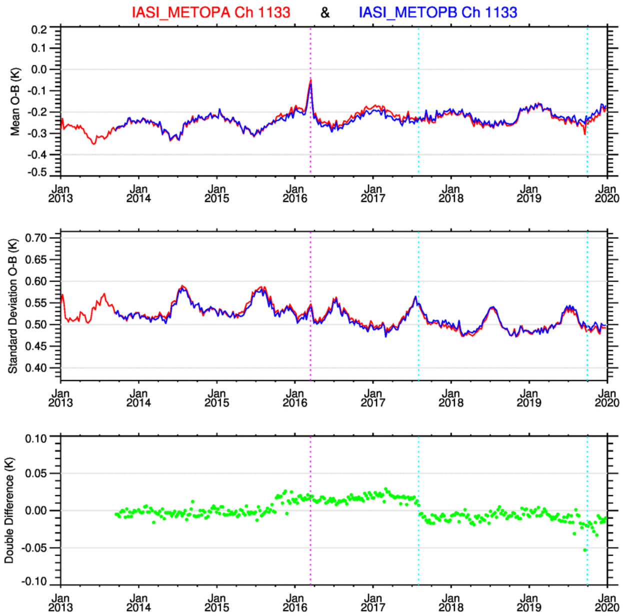

Fig. 1. Time series of Observed-Background IASI radiances from Metop-A and Metop-B window channel at 928 cm^{-1} (10.8 μm) showing (Top) global mean, (Middle) standard deviation, and (Bottom) double difference of IASI-A minus IASI-B. The dotted lines show when changes were made to the IASI calibration (blue) and varBC was introduced (red).

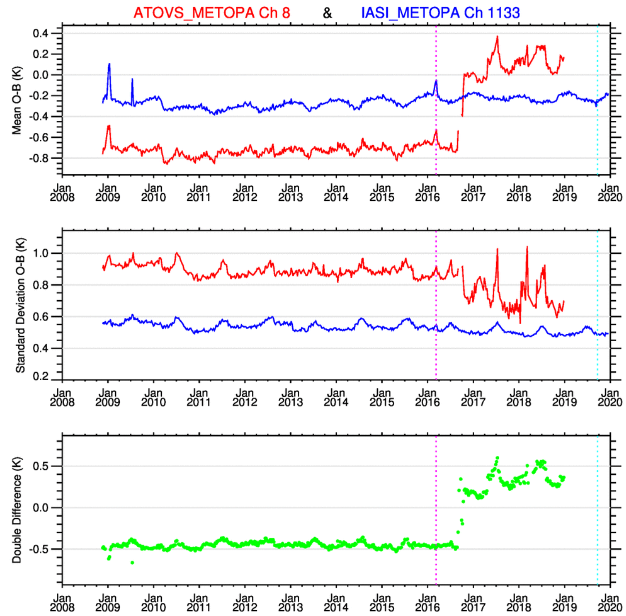

Fig. 2. Time series of Observed-Background IASI and HIRS radiances from Metop-A for the IASI window channel at 928 cm^{-1} (10.8 μm) and HIRS channel 8 showing (Top) global mean, (Middle) standard deviation, and (Bottom) double difference of HIRS minus IASI-A. The dotted lines are as in Fig. 1.

hard to see the difference between both IASI instruments in these plots. There is a clear annual cycle in both the bias and standard deviation with variations in bias of typically 0.1 K probably due to changes in the model surface and low-level water vapor fields. Similar annual cycles are seen by other instruments (see Fig. 3). A peak in the bias in early 2016 is from the introduction of variational bias correction [17] at the Met Office on March 14, 2016 which affected the model fields. The standard deviation has decreased slowly throughout the period which can be attributed to an improvement in the low-level water vapor field of the model. The double difference plot in the bottom panel of IASI-A minus IASI-B O-B values clearly demonstrates how close both instruments are with a globally averaged mean difference between the two instruments of between 0 and 0.02 K. This demonstrates how stable and well calibrated the IASI instruments are, giving climate-quality radiance measurements. There are three discrete changes in the difference worthy of mention in October 2015, August 2017, and September 2019. The latter two events were after updates to the IASI-B and IASI-A nonlinearity corrections, respectively, [18] which reduced the bias between both sensors to 0.01 K. The reason for the event in 2015 is still unclear and comparisons with other analyses [8], [9] show no jumps in the IASI-A time series, suggesting it is an undocumented change in the NWP model.

Fig. 2 shows an example of the HIRS window channel 8 on Metop-A compared with an IASI channel centered on the HIRS channel 8 spectral response at 928 cm^{-1}. The bias and standard deviation seen in the HIRS measurements are much larger than for IASI but up to 2015 most changes in the bias were mirrored in both sensors, resulting in the double difference (bottom panel) being nearly stable. However, during late 2016, the HIRS bias and standard deviation for channel 8 started to vary significantly due to jitters in the rotation of the filter wheel and so the channel was blacklisted in the operational systems. This is an example where the double difference in the bottom panel shows when an instrument starts behaving anomalously.

The same monitoring was applied to the Meteosat SEVIRI imager channels and compared with sounders on polar orbiters for the same area viewed by SEVIRI. Fig. 3 shows in the top panel for the 10.8 μm window channel of SEVIRI the mean biases over the ten-year period of several different Meteosat platforms (Meteosat-9–11). Note that only one SEVIRI at a time could be monitored. On the same plot are the polar orbiter sounder radiance O-B values for those channels with a similar spectral response averaged over the primary Meteosat full disk area centered on 0°N 0°E. The biases for the three SEVIRI instruments are all similar but not identical being cooler than the modeled radiance (typically -0.3 K) and exhibit some variability which is mainly linked to the annual cycle. All the IASI instruments have a similar bias to SEVIRI with similar variability, showing it is the bias in the NWP fields that is varying, not the instruments. The IASI biases shown in Fig. 3 are similar to those seen in the ECMWF ERA-5 monitoring [8]. This also confirms that the SEVIRI calibration is working well as IASI can be considered a good reference calibration source. The HIRS sounders all have a much larger negative bias (~ -0.8 K) until mid-2013 but are very consistent between them on the NOAA platforms and Metop-A HIRS. The exception is the Metop-B HIRS which had a lower bias similar to IASI but the standard deviation was large (not shown), so clearly this HIRS was not operating as expected. The HIRS on NOAA-19 also showed a sudden

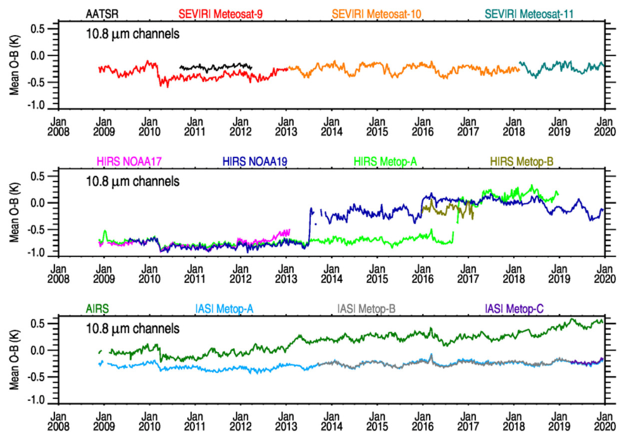

Fig. 3. Time series of Observed-Background Meteosat, IASI, AIRS, AATSR, and HIRS radiances for the 10.8 μm window infrared channels showing the mean over the Meteosat full disk area.

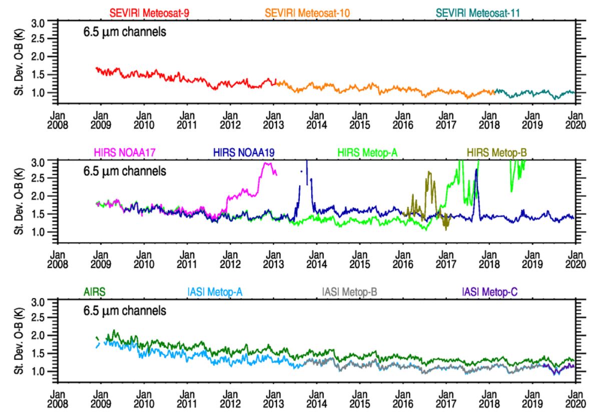

Fig. 5. Time series of standard deviation of Observed-Background Meteosat, IASI, AIRS, and HIRS radiances for the 6.5 μm water vapor channels over the Meteosat full disk area.

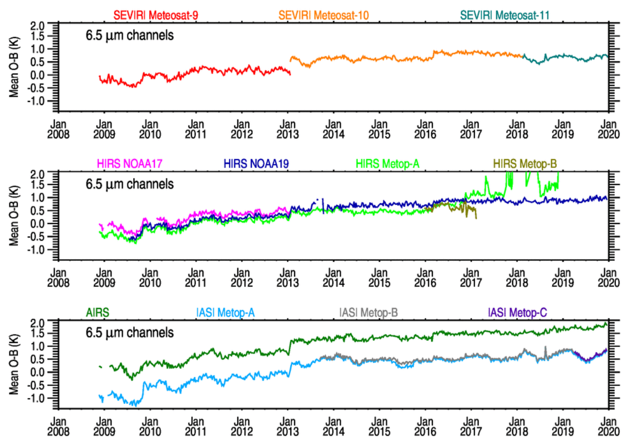

Fig. 4. Time series of Observed-Background Meteosat, IASI, AIRS, and HIRS radiances for the 6.5 μm water vapor channels over the Meteosat full disk area.

large decrease in the bias in 2013 accompanied by an increase in the standard deviation of the difference. The AIRS bias in 2008 was close to zero but this has gradually increased over the ten years to 0.4 K and has also increased relative to IASI radiances in recent years. Other analyses [10], [11] show that these channels in AIRS are stable to 0.01 K per year and so the increasing bias seen here is probably due to the higher water vapor emission in the AIRS channel relative to the IASI channel. Finally, the AATSR biases for the short period from 2010 to 2012 were fairly stable at −0.2 K but 0.1 K warmer than the IASI bias which is worth noting as the AATSR design prioritized high radiometric calibration accuracy for sea surface temperature retrievals. However, the effectiveness of the cloud detection is another factor which can affect the difference in bias between the instruments.

Fig. 4 shows the time series for the water vapor channels around 6.5 μm (1540 cm^{-1}) over the Meteosat area. The first thing to note is that all the radiance biases are increasingly positive over the ten-year period, although the rate slows after 2015. This is due to a gradual moistening of the NWP model fields over the years but now the radiance biases suggest there is too much water vapor in the model fields. There are also some jumps in the bias seen by all the instruments, and these are due to changes in the NWP system. Comparing the biases, the IASI instruments are very close in their bias, but AIRS appears to have a bigger positive bias of 0.8 K warmer than IASI which may partly be due to the different wavelengths of the channels. The HIRS radiances from different platforms are all within 0.2 K of the IASI radiances since 2014 with the exception of the HIRS on Metop-A which from 2017 have large differences and standard deviations compared with the model. Fig. 5 shows the standard deviation of the difference for the Meteosat area which clearly shows when the individual HIRS instruments fail or show anomalous behavior. All the HIRS instruments have shown anomalies during the period. The other feature is the gradual reduction in the standard deviation of the water vapor channels from SEVIRI, IASI, and AIRS over the period showing that the NWP model's representation of upper tropospheric water vapor has improved over the years. It is noteworthy that the standard deviation for SEVIRI is slightly lower than for IASI and AIRS (∼0.1 K) which is likely to be because SEVIRI "sees" a deeper atmospheric layer which will average some of the variability seen by IASI/AIRS. The AIRS standard deviation of the O-B difference is marginally greater than for IASI which can be accounted for by the different noise and different channel spectral responses relative to the water vapor lines. The different overpass times of AIRS and IASI may also contribute to this, with greater model uncertainties close to the early-afternoon orbit.

Fig. 6 is a plot for the Meteosat area for the carbon dioxide absorption channels at 14.2 μm (706 cm^{-1}) for AIRS and several HIRS and IASI instruments. The Meteosat SEVIRI CO_2 channel is included at a shorter wavelength (13.4 μm, 748 cm^{-1}) and is sensitive to the surface. The striking feature on this plot is the impact of ice build-up on the SEVIRI detectors, which causes a change in this channel's spectral response function [19]. This change is not taken into account in the RT model as it is not well understood and so the O-B values decrease with time as shown clearly by SEVIRI on Meteosat-9. The Meteosat-10 mean bias illustrates the impact

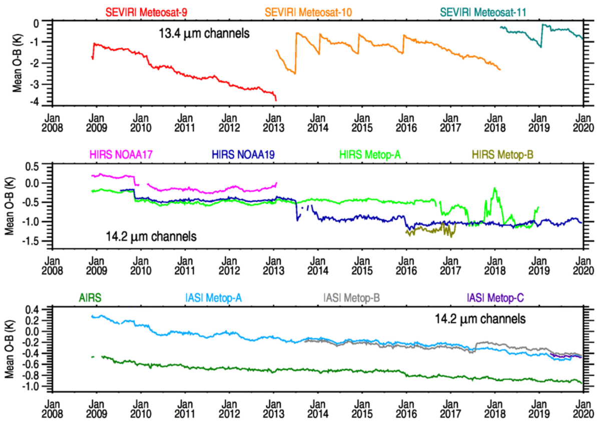

Fig. 6. Time series of Observed-Background IASI, AIRS, and HIRS radiances for the 14.2 μm carbon dioxide channels and for SEVIRI, the 13.4 μm channel showing the mean over the Meteosat full disk area.

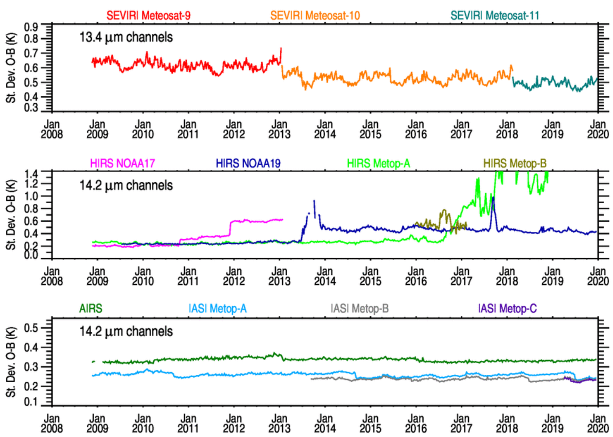

Fig. 7. Time series of standard deviation of Observed-Background IASI, AIRS, and HIRS radiances for the 14.2 μm carbon dioxide channels and for SEVIRI the 13.4 μm channel showing the mean over the Meteosat full disk area.

of the periodic decontamination to remove the ice, which then reduces the bias. The biases for the polar orbiting sounders become slightly more negative over the ten years due to NWP system changes and increasing carbon dioxide not accounted for in RTTOV. The three IASI instruments are very consistent with the same bias close to zero, which has a trend of −0.05 K per year due to increasing CO_2 not accounted for in the model radiances. The IASI nonlinearity corrections [18] are also more evident at these longer wavelengths with an increase in the Metop-B bias relative to Metop-A in August 2017 which is decreased when Metop-A is corrected in September 2019 with Metop-C having a very similar bias to the other IASIs.

AIRS has a mean bias over the decade close to −0.7 K with a negative trend of around −0.06 K per year, which is similar to other studies [11]. The larger bias for AIRS is due to the CO_2 concentration assumed in the RT model for AIRS being different from the IASI calculations. The ERA-5 monitoring [8] also has a decreasing bias of −0.06 K per year for this AIRS channel. For the HIRS instruments, NOAA-19 and Metop-A started with similar biases around −0.5 K and NOAA-17 HIRS at −0.2 K. However, in mid-2013, the NOAA-19 HIRS bias jumped to −1 K with an associated increase in standard deviation, as shown in Fig. 7. This is most likely caused by erratic behavior of the filter wheel. The Metop-A HIRS bias was stable until late 2016 when the bias became variable and the standard deviation increased. The HIRS on NOAA-17 failed in early 2013 after several increases in noise shown in Fig. 7. The Metop-B HIRS bias was stable during 2016 but then became erratic in early 2017 and was no longer monitored.

Fig. 7 shows the standard deviation of the CO_2 channel O-B differences for the Meteosat area and a few things can be noted. Firstly, for SEVIRI, the gradual reduction in the standard deviations is partly due to Meteosat-9 having larger O-B biases (see Fig. 6) than Meteosat-10/11 as the decontamination of the detector to revert the spectral response to the nominal profile was not done for Meteosat-9. SEVIRI standard deviations also show a seasonal variation in the standard deviation, which may be due to increased sensitivity to the surface for these channels. The jumps in the HIRS standard deviations are clear when the radiometer starts to behave anomalously. Both AIRS and IASI have stable standard deviations over the past decade, indicating the instruments are stable and the NWP model upper tropospheric temperature profiles have remained stable in their errors. There are a few unexplained small reductions (∼0.02 K) in the Metop-A and Metop-B IASI values in the time series but this is not seen in the other shorter wavelength channels of IASI.

IV. Summary

Over ten years of monitoring of satellite imagery and sounder infrared channels using the global Met Office NWP fields is presented here to show the stability of these instruments with time. This is valuable for the production of fundamental climate data records and also for assimilation in reanalysis. This work extends in time the analysis reported earlier [7] where the bias was examined for various different variables such as scan angle and scene temperature. Only the time series are reported here as the other bias statistics have not changed. Three wavelengths were chosen to assess the instruments, the window infrared channel at 10.8 μm, the water vapor channel at 6.7 μm, and the carbon dioxide channels at 14.2 μm (13.4 μm for SEVIRI). Some comparisons have been made with other monitoring centers against ECMWF reanalysis [8] and the GSICS monitoring by JMA [9].

The mean O-B differences for IASI on Metop-A and Metop-B are almost the same for all three channels plotted here throughout the 2013–2019 time period. The standard deviation of the difference of the IASI water vapor channels shows a decrease over the ten years, demonstrating an improved representation of the upper tropospheric water vapor field in the Met Office NWP model. Also, the mean bias for all the sensors has become more positive with time due to a moistening of the NWP model's upper tropospheric humidity.

AIRS radiances have been stable over the ten years but have mean biases significantly different from IASI by up to 1 K, which may be related to the RT model or a diurnally varying bias of the model fields as both instruments sample the diurnal cycle at different times of the day. This analysis includes a short period of AATSR radiances, which has a refined on-board calibration system, and shows a mean difference in between AIRS and IASI for its 10.8 μm channel.

The IASI and AIRS radiance measurements will make good FCDRs as they are shown to be stable and have only small biases when compared with global NWP simulations. A fundamental climate data record which goes back to 2002 should be generated for AIRS, although some investigation of the instrument biases needs to be undertaken by comparing with CrIS and IASI. The HIRS and Meteosat radiances will need more care to produce stable FCDRs due to changes in instrument performance over time. The HIRS instruments, designed many years ago, exhibit similar biases until the filter wheel jitter occurs and then the O-B values and standard deviation change significantly rendering the instrument unsuitable for use for periods as illustrated in Figs. 2–7. Metop HIRS instruments were blacklisted from the Met Office NWP assimilation in 2016. Creating FCDRs from the HIRS level 1B radiances will need careful reprocessing but given the long time series of HIRS (back to the mid-1970s), it is a valuable data set. In some cases, after a filter wheel jitter, the instrument does settle down again and can be used again. The HIRS on Metop-B is in this category but unfortunately in our processing, it was removed when it became anomalous.

The O-B differences of the CO_2 channels on SEVIRI, IASI, and AIRS/HIRS are all different due to instrument-related calibration and spectral response function errors. The problems of ice build-up increasing the O-B difference on the SEVIRI 13.4 μm channels are clearly shown as is the impact of the occasional decontamination for Meteosat-10 and 11 to reduce this difference by up to 2 K.

Ideally, similar plots for CrIS on both Suomi-NPP and NOAA-20 could be added to this analysis but these have a shorter time series to date and were not included in the original processing.

Acknowledgment

The satellite data were provided by EUMETSAT, ESA, and NOAA as part of the real-time delivery of data to the Met Office for its operational data assimilation.

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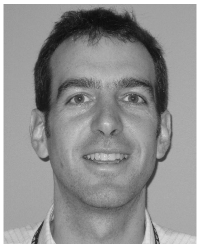

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